

Chapter 1

An Overview of SIMBIOS Program Activities and Accomplishments

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1.1 INTRODUCTION

The SIMBIOS Program was conceived in 1994 as a result of a NASA management review of the agency's strategy for monitoring the bio-optical properties of the global ocean through space-based ocean color remote sensing. At that time, the NASA ocean color flight manifest included two data buy missions, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Earth Observing System (EOS) Color, and three sensors, two Moderate Resolution Imaging Spectroradiometers (MODIS) and the Multi-angle Imaging Spectro-Radiometer (MISR), scheduled for flight on the EOS-Terra and EOS-Aqua satellites. The review led to a decision that the international assemblage of ocean color satellite systems provided ample redundancy to assure continuous global coverage, with no need for the EOS Color mission. At the same time, it was noted that non-trivial technical difficulties attended the challenge (and opportunity) of combining ocean color data from this array of independent satellite systems to form consistent and accurate global bio-optical time series products. Thus, it was announced at the October 1994 EOS Interdisciplinary Working Group meeting that some of the resources budgeted for EOS Color should be redirected into an intercalibration and validation program (McClain *et al.*, 2002).

NASA Goddard Space Flight Center (GSFC) was directed to develop an intercalibration and validation program plan for submission to NASA Headquarters (HQ) by May 1995. This plan envisioned a Science Team funded by a NASA Research Announcement (NRA) (released in July 1996) and the SIMBIOS Project Office that was established at GSFC in January 1997. The initial SIMBIOS Program was scoped for five years (1997-2001) and included separate support for a science team and the Project Office. Dr. Mueller (San Diego State University) acted as an interim project manager at GSFC under a one-year assignment to assist in getting the project office organized and the science team contracts executed. During the second year of the SIMBIOS Project, Dr. McClain assumed project management for SeaWiFS and SIMBIOS, as both Dr. Cleave and Dr. Mueller stepped down in their roles as project managers of these two projects, respectively. In fall 1998, Dr. Fargion was hired as Deputy Project Manager to assist Dr. McClain.

In September 2000, Dr. McClain assumed new responsibilities in assisting HQ to develop a long-term program for global carbon cycle research. As a result, SeaWiFS and SIMBIOS Project Office were reorganized somewhat to allow Dr. McClain to focus on the carbon initiative. Dr. Feldman assumed management responsibilities for SeaWiFS and Dr. Fargion for SIMBIOS, respectively. Due to the success of the SIMBIOS Program combined with a strong collaboration with the US and international ocean communities, HQ release a second NRA (1999) and granted an extension of three years to the project. However, in 2002, NASA HQ decided to discontinue the program in its present form. The rationale centered on three considerations. The first was a desire by HQ to integrate the various ocean color calibration and validation activities of the SIMBIOS, SeaWiFS, and the MODIS programs under a common ocean color team which would also include investigators supported under the NASA Ocean Biogeochemistry program. While the three ocean color projects have separate management and funding structures, they have been coordinated and mutually supportive with little redundancy. The second consideration stems from initial problems with MODIS ocean data quality and accessibility which has made it imperative for NASA to focus its available resources on MODIS ocean calibration and validation.

The third consideration is the preparation for ocean color observations from the Visible-Infrared Radiometer Suite (VIRIS) on National Polar Orbiting Environmental Satellite System (NPOESS) Preparatory Project (NPP), which is scheduled to launch in 2006.

The SIMBIOS Project Office, co-located with the SeaWiFS Project Office, provides support and coordination for the SIMBIOS Program, such as administration, project documentation, and interagency and international coordination. It also incorporates aspects of post launch calibration and characterization, *in situ* data collection, protocol developments, round robins, algorithm development and evaluation, product merging, and data processing (Figure 1.1 and Table 1.1). All components illustrated in Figure 1.1 are tightly connected (and in some cases overlap) and were thoroughly developed and integrated by the Project during the operational years (1997-2003).

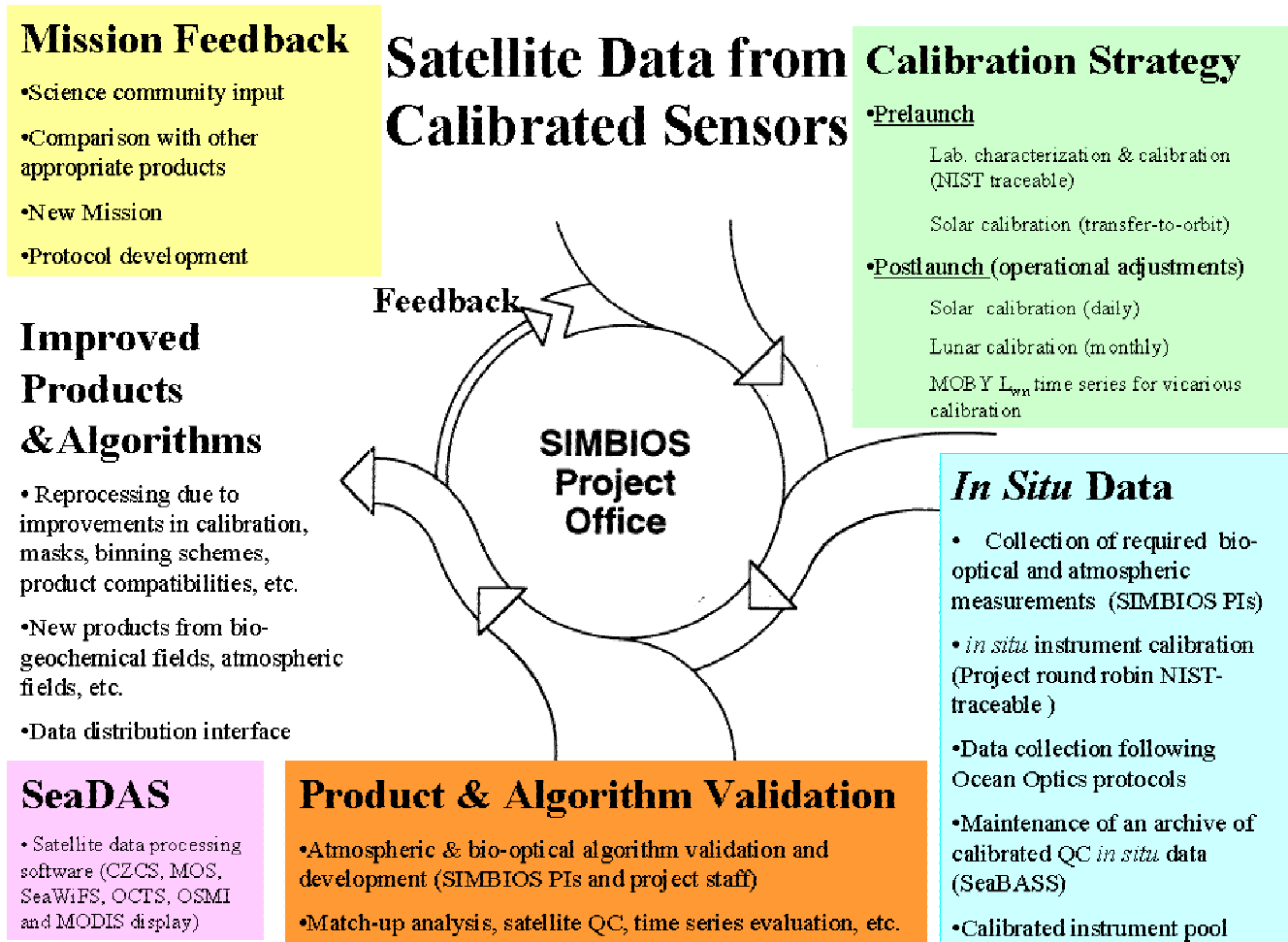


Figure 1.1: SIMBIOS Project activity areas

The specific proposed objectives of the SIMBIOS Program were: (1) to quantify the relative accuracy of measurements from the ocean color products from each mission, (2) to work with each project to improve the level of confidence and compatibility among these products, and (3) to develop methodologies for generating merged level-3 products. These objectives became operational. In particular, the intercomparison component performs many functions similar to those being performed by each individual mission (calibration, validation, quality control, algorithm development and data processing) but does so by integrating information from each project, augmenting activities where required, providing feedback to each project and the ocean color community, and coordinating with the international community. The program requirements were identified as:

- Field measurement and data processing protocol definition and development
- Global bio-optical and atmospheric *in situ* data collection
- Bio-optical and atmospheric database development (SeaBASS)
- Traceability of laboratory calibration sources to standards (round robin)
- Instrumented calibration sites (MOBY)
- Prelaunch sensor calibration and characterization protocols
- On-orbit calibration evaluation and methodology development
- Bio-optical and atmospheric correction algorithm development
- Product accuracy evaluation and methodology development
- Data merger algorithm development and data processing
- High volume data processing capabilities
- Technology evaluation and development (SQM)
- Multi satellite data processing software
- Systematic documentation (NASA technical memorandum and publications)

SIMBIOS has worked with several missions, such as SeaWiFS, Ocean Color and Temperature Scanner (OCTS), Polarization and Directionality of the Earth's Reflectances (POLDER), Modular Optoelectronic Scanner (MOS), Ocean Scanning Multispectral Imager (OSMI), MODIS (Terra and Aqua), Medium Resolution Imaging Spectrometer (MERIS) and Global Imager (GLI). The Project staff ensured the development of internally consistent research products and time series from multiple satellite ocean color data sources; developed methodologies for cross-calibration of satellite ocean color sensors; developed methodologies for merging data from multiple ocean color missions; promoted cooperation between ocean color projects, and served as a prototype for future Earth observation programs. In order to better communicate with the community, the project held annual open science team meetings and workshops, participated as a member in several mission teams, documented all activities in NASA technical memorandum (TM) and hosted a web site organized to serve as the main information resource of Project activities, the Project Office, and the Science Team. The Project Office, in an effort to educate and promote the concept of an organized program of sensor cross-calibration and validation, has sent representatives to several international conferences. The objectives, and activities of SIMBIOS are discussed in more detail in a number of documents including the SIMBIOS Project Annual Reports (McClain and Fargion, 1998 & 1999; Fargion and McClain 2000, 2001 & 2002), the Ocean Optics Protocols TMs (Mueller & Fargion, 2003; Fargion *et al.*, 2001) and round robin reports (Riley and Bailey 1998; Meister *et al.*, 2002 & 2003; Van Heukelem *et al.* 2002) and others cited in this chapter.

Table 1.1: SIMBIOS Project Activities and Responsible Staff

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| <ul style="list-style-type: none"> • Satellite Data Processing
Bryan Franz, Joel Gales, Sean Bailey and SeaWiFS staff • Satellite Characterization
Bob Barnes and Gerhard Meister • Data Merging
Ewa Kwiatkowska-Ainsworth and Bryan Franz • Support Services
Sean Bailey, Jeremy Werdell, Christophe Pietras and Kirk Knobelspiesse • Data Product Validation
Sean Bailey, Jeremy Werdell, Christophe Pietras and Kirk Knobelspiesse • Calibration Round Robin
Gerhard Meister and Bob Barnes |
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1.2 SIMBIOS SCIENCE TEAM

The SIMBIOS Science Team was selected through NRA's 1996 and 1999. NASA HQ manages the process of team selection, but the GSFC NASA Procurement Office handles the team contracts, work

statements and, if necessary, budget negotiations. The Project funds numerous US investigators and collaborates with several international investigators, space agencies [e.g., National Space Development Agency of Japan (NASDA), European Space Agency (ESA), Korea Aerospace Research Institute (KARI)] and international organizations [e.g., International Ocean Colour Coordinating Group (IOCCG), Joint Research Center (JRC)]. US investigators under contract provide *in situ* atmospheric and bio-optical data sets, and develop atmospheric correction and bio-optical algorithms and methodologies for data merger schemes. NASA Procurement requires formal evaluations for all contracts at the end of each contract year. These evaluations go into a database and are shared with the PI's institution or upper management. The locations of specific SIMBIOS team investigations are shown in Figures 1.2 and 1.3.

The international ocean color community's response to NRA-99 was overwhelming: a total of 75 PI's proposed collaborations with the Project. The twelve international proposals covered topics ranging from protocols, calibration-validation activities, atmospheric-biological algorithms, and data merging. The SIMBIOS Science Team meetings were held in August 1997 at Solomons Island (Maryland), in September 1998 at La Jolla (California), in September 1999 at Annapolis (Maryland), in January 2001 at GSFC (Maryland), and in January 2002 at Baltimore (Maryland). SIMBIOS Science meetings had large US and international contingents, including participants from space agencies and international organizations. During each year, the Project has hosted several US and international visiting scientists (e.g., Dr. Antoine, Dr. Deschamps, Dr. Frouin, Dr. Fukushima, Dr. Hagolle, Dr. Kopelevich, Dr. Miller, Dr. Nicolas, Dr. Souaidia, Dr. Subramaniam, Dr. Tanaka, Dr. Yamamoto and Dr. Zibordi), staying from 2 weeks to one year at GSFC.

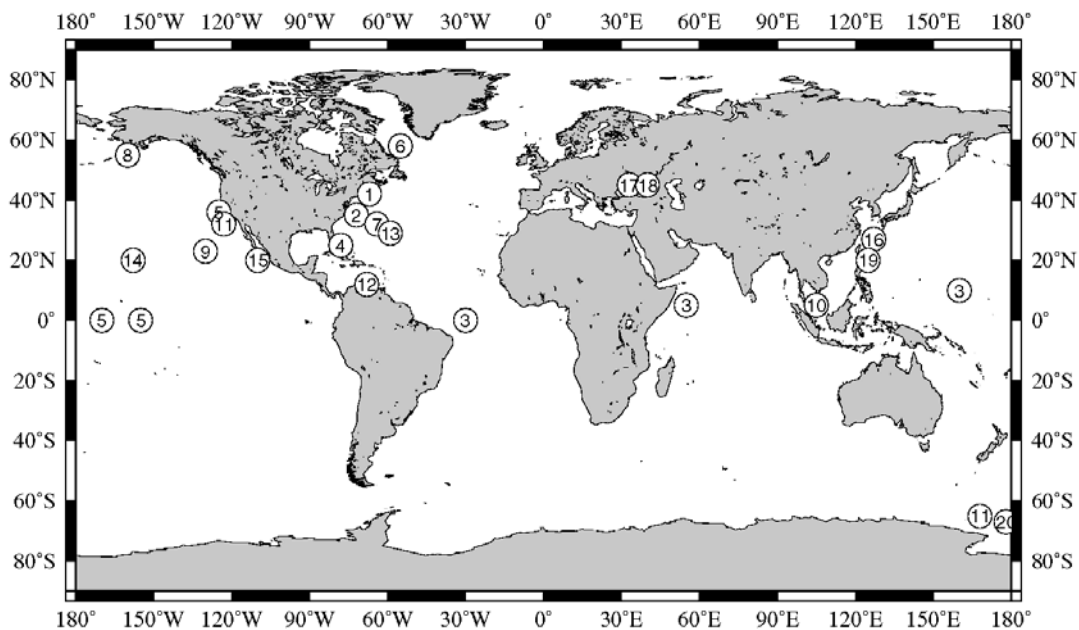


Figure 1.2: Global distribution of the NRA-96 selected SIMBIOS studies. United States (field): (1) Balch; (2) Brown/Brock; (3) Capone/Carpenter/Subramaniam and Miller; (4) Carder and Green; (5) Chavez; (6) Cota; (7) Dickey; (8) Eslinger; (9) Frouin; (10) Miller; (11) Mitchell and Green; (12) Müller-Karger; (13) Siegel; (14) Porter (15) Zaneveld and Mueller. United States (theoretical): Flatau; Siegel and Stamnes/Chen. International: He; Korotaev; Kopelevich; and Li.

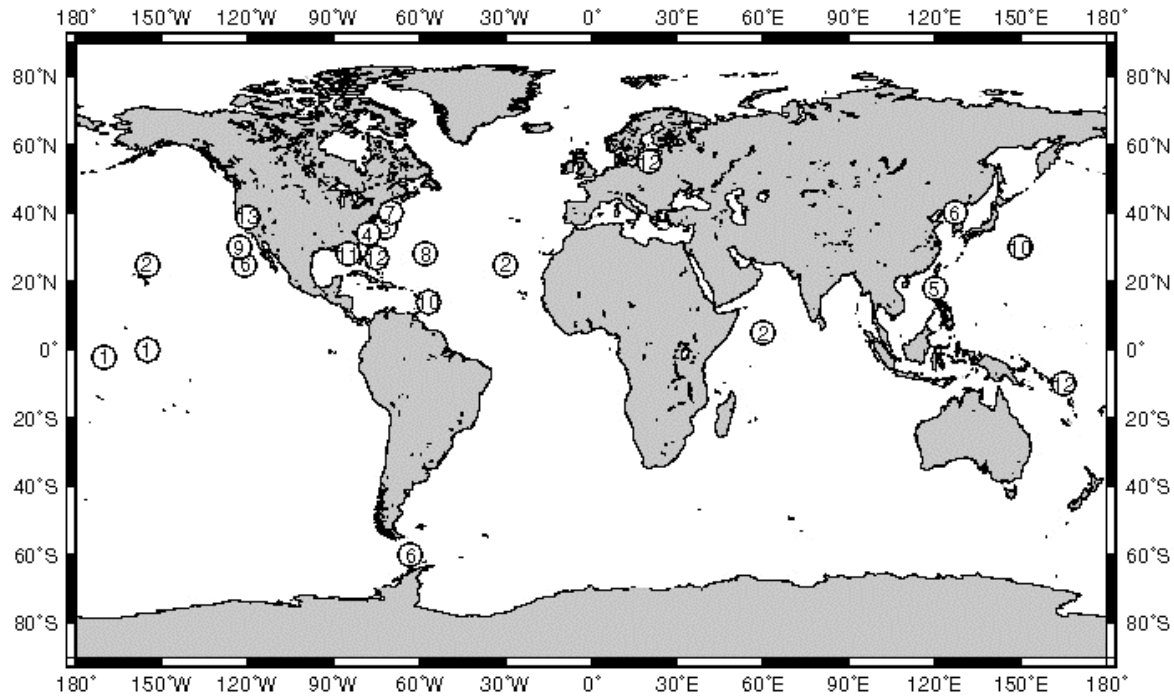


Figure 1.3: Global distribution of the NRA-99 selected SIMBIOS studies. United States (field): (1) Chavez; (2) Frouin; (3) Gao; (4) Harding; (5) Miller; (6) Mitchell; (7) Morrison; (8) Nelson; (9) Siegel; (10) Spinhirne; (11) Stumpf; (12) Subramaniam; (13) Zalewski. United States (theoretical): Gregg; Hooker; Maritorena; Mueller; Trees and Wang. International: Bohm; Zibordi; Fougnie; Deschamps; Antoine; Kopelevich; Ishizaka; Fukushima; Chen; Li & Lynch.

1.3 OCEAN COLOR SATELLITE DATA PROCESSING

Over the past several years, the SIMBIOS Project has been engaged in the characterization, validation, intercomparison, and cross-calibration of a host of space-borne ocean color sensors (Table 1.2 and Table 1.3). This work has included the characterization and calibration of OCTS and POLDER (Wang *et al.*, 2002), the cross-calibration and long-term intercomparison of MOS and SeaWiFS (Franz *et al.*, 2001; Wang and Franz, 2000), the cross-calibration of OSMI to SeaWiF (Franz and Kim, 2001), and the intercomparison of MODIS/Terra (Fargion and McClain, 2003b) and MODIS/Aqua with SeaWiFS, as well as independent validation of MODIS (Terra & Aqua), SeaWiFS, OCTS, and POLDER using coincident *in situ* measurement archived in SeaWiFS Bio-optical Archive and Storage System (SeaBASS).

To facilitate the processing and intercomparison of ocean color products from multiple instruments, the SIMBIOS Project developed atmospheric correction code based on the SeaWiFS algorithm of Gordon and Wang (1994). The approach was to identify those few parts of the algorithm that were sensor or band-pass specific, and develop a software package that could process data from multiple ocean color sensors with minimal changes in the algorithms. The sensitivity of the atmospheric correction algorithm to differences in spectral bands was carefully assessed by Wang (1999), wherein he showed by simulation that these differences could be accurately accounted for through exact calculation of the Rayleigh reflectances and minor modifications to the diffuse transmittance calculation. The multi-sensor level-1 to level-2 code (MSL12) has been used to process data from MOS, OCTS, POLDER, OSMI, and SeaWiFS, with support

for MODIS currently underway. Due to its enhanced flexibility and maintainability, the software was adopted by the SeaWiFS Project for all standard production, calibration, and validation activities and is widely distributed and utilized by the international ocean color community through the SeaWiFS Data Analysis System (SeaDAS).

Table 1.2: Satellite data supported (1997-2003).

- MOS-SeaWiFS cross calibration and data merger with SeaWiFS
 - German Aerospace Research Establishment (DLR)
- MOS data acquisition at NASA Wallops Flight Facility
 - Indian Space Research Organization (ISRO)
- OCTS-POLDER cross calibration
 - National Space Development Agency of Japan (NASDA)
 - Centre National d'Etudes Spatiales (CNES), France
- OCTS global GAC reprocessing
 - NASDA
- OSMI-SeaWiFS cross calibration and data processing
 - Korean Aerospace Research Institute (KARI)
- SeaWiFS calibration and product validation
- MODIS (Terra & Aqua) product validation
- MODIS (Terra & Aqua) data merger with SeaWiFS (9km Chlorophyll product and diagnostic data set)
- MERIS calibration and product validation (MOBY)
 - European Space Agency (ESA)
- GLI characterization and field calibration cruise
 - NASDA

Table 1.3: Work done by sensor (1997-2003).

	Satellite Characterization	<i>in situ</i> matchups	L_w , & chlorophyll	MOBY	AOT
MOS	✓		✓		
OCTS	✓		✓		
POLDER	✓		✓		
SeaWiFS	✓		✓	✓	✓
OSMI	✓		✓	✓	
GLI	✓				
MODIS (Terra)	✓		✓	✓	✓
MODIS (Aqua)	✓		✓	✓	✓

The SIMBIOS Project, using MSL12, performed an independent vicarious calibration of the OCTS sensor, then reprocessed the entire global OCTS mission archive (Figure 1.4). This data was distributed through the Goddard DAAC, with processing and display support distributed through SeaDAS. This provided the ocean color community with a nearly complete, highly compatible ocean color time-series from September 1996 to the present day, including the first complete record of an El Niño/La Nina event. The SIMBIOS Project also developed and evaluated methods for cross-calibration of ocean color sensors, beginning with the MOS and SeaWiFS instruments. The MOS is a German ocean color sensor flying on the Indian Space Agency IRS-P3 satellite. Because the sensor has a small swath width of 192 km and only four ground stations capable of receiving the real time-only transmissions, there is limited opportunity for ground truth. In addition, the sensor is a push-broom CCD array with 384 independent detectors in each band, so calibration requires both a cross-scan, detector-relative calibration and an absolute calibration. As a prototype for future missions, the SIMBIOS Project developed a technique to vicariously calibrate MOS

using SeaWiFS (Wang and Franz, 2000). The method is analogous to that used by the SeaWiFS Project for vicarious calibration to MOBY, except that for MOS the Project used SeaWiFS observations rather than MOBY measurements as truth. A major advantage of this technique is that the Project was able to obtain a large number of matchups for each detector of each band, and thus derive both the absolute and detector-relative calibrations simultaneously. This vicarious cross-calibration, coupled with the instrument calibration performed by the MOS Project, has enabled the retrieval of oceanic optical properties which maintain good agreement with SeaWiFS, even after three years (Wang *et al.*, 2001).

The SIMBIOS Project performed a similar cross-calibration between SeaWiFS and OSMI (Franz and Kim, 2001). OSMI is a whisk-broom scanning CCD array with 96 detectors per band distributed along track. The detectors are divided into two independently amplified fields of 48-detectors each. Prior to cross-calibration, the calibrated level-1B radiances exhibited significant interdetector striping, banding between the detector fields, and absolute radiances that were below the predicted Rayleigh radiance in most bands. As such, it was not even possible to compute oceanic optical properties, as any atmospheric correction would fail. In this case, it was necessary to develop a calibration for the NIR channels as well as the visible bands. The NIR calibration was performed using the SeaWiFS retrieved aerosol optical thickness as truth, using a technique originally developed to calibrate SeaWiFS to in situ aerosol optical thickness measurements (Franz *et al.*, 2001). Once the NIR calibration was established, the calibration of the visible bands proceeded in a manner analogous to the MOS-to-SeaWiFS cross-calibration, with independent gains derived for each detector of each band. After this cross-calibration it was possible, for the first time, to process an OSMI scene and retrieve meaningful oceanic optical properties.

The final year of the SIMBIOS Project was largely dedicated to MODIS analyses. An extensive evaluation of the temporal trends in several standard ocean color products derived from SeaWiFS and MODIS/Terra was performed to determine the long-term relative stability between the two sensors and to develop an understanding of their similarities and differences. This time-series analysis investigated variations in the mean value of water-leaving radiance and chlorophyll products over the period from March 2000 through December 2002, for both global and regional geographic areas, between MODIS Collection #4 and SeaWiFS Reprocessing #4. The analysis was able to demonstrate the remarkable temporal stability of SeaWiFS, and assess the long-term stability of MODIS/Terra (see http://simbios.gsfc.nasa.gov/simbios_modis.html; Fargion & McClain, 2003b). This work on these various sensors has provided critical insight into the issues and limitations associated with the establishment of a long-term, multi-mission, climate data record for ocean color.

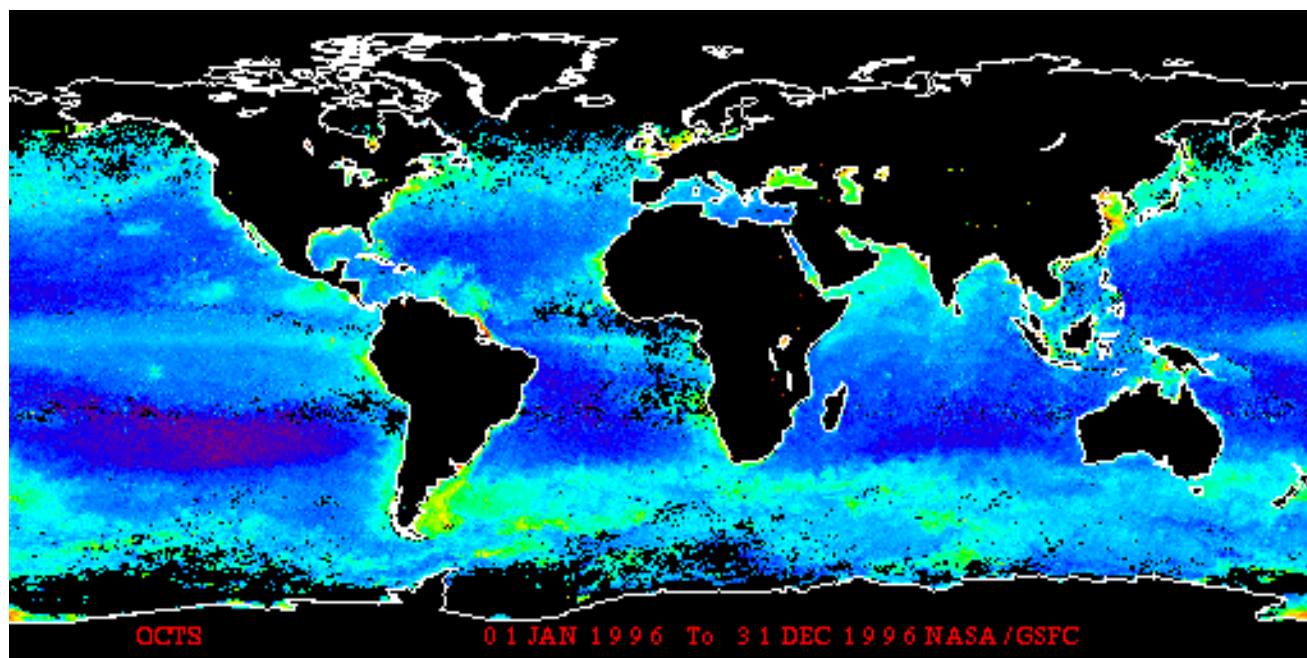


Figure 1.4: Retrospective satellite data processing reprocessing of OCTS GAC mission archive

1.4 DATA MERGER

The objective of ocean color data merger is to create a consistent series of systematic ocean color measurements from multi-instrument, multi-platform and multi-year observations based on accurate and uniform calibration and validation over the lifetime of the measurement. The most obvious benefit of data merger is improvement in spatial and temporal ocean color coverage. Data merger is the ultimate tool for the creation of ocean color climate data records. The major data merger effort undertaken by the SIMBIOS Project focused on integrating daily MODIS/Terra and SeaWiFS chlorophyll data sets. MODIS and SeaWiFS data were used to study methodologies to create a consistent series of long-term observations from sensors of different design, characterization, processing algorithms, and calibrations. Analyses of MODIS/Terra (Kilpatrick *et al.*, 2002; Fargion and McClain, 2003) daily oceans data in comparison with SeaWiFS were performed to facilitate the merger efforts (<http://simbios.gsfc.nasa.gov/~ewa/SeaMODIS/seamodis-match.html>). The analyses focused on assessing temporal trends in data discrepancies between MODIS and SeaWiFS and artifacts present in MODIS data caused by the difficulties in accurately characterizing this complex sensor for features such as polarization sensitivity. A time series of daily water-leaving radiance and chlorophyll products, evenly spread over the three years of joint MODIS/Terra and SeaWiFS coverage, was used to study MODIS trends in departure from SeaWiFS data and MODIS scan angle and latitudinal dependencies. Corresponding investigations were performed on a three-month time series of provisional MODIS/Aqua data and concurrent SeaWiFS coverage (<http://simbios.gsfc.nasa.gov/~ewa/SeaMODISAqua/seamodis-aqua.html>). The analyses provided vital information on MODIS data dependencies in relation to SeaWiFS ocean color records for the data merger activity. The information derived from MODIS/Terra and SeaWiFS comparisons was used to derive an ocean color sensor cross-calibration strategy where sensor artifacts, temporal, and spatial variabilities are not easily quantifiable and many dependencies are involved. Machine learning techniques were developed to cross-calibrate MODIS/Terra and SeaWiFS and produce a consistent ocean color baseline data set. The cross-calibration enabled the production of combined MODIS and SeaWiFS daily global chlorophyll coverages which were free from temporal trends, as well as MODIS scan angle and latitudinal dependencies (Kwiatkowska, 2003). An example of the cross-calibration result is shown in Figure 1.5.

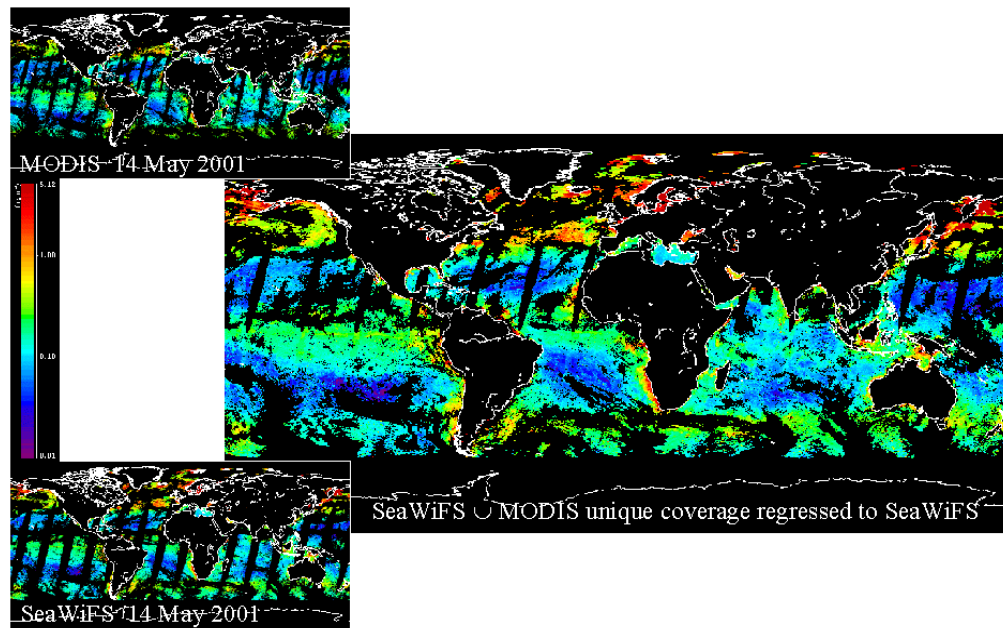


Figure 1.5: Result of machine learning cross-calibration of MODIS and SeaWiFS data. A merged, consistent daily chlorophyll map was produced using original SeaWiFS chlorophyll and MODIS data regressed to SeaWiFS baseline chlorophyll representation.

Statistical objective analysis was investigated to spatially and temporally interpolate MODIS/Terra (cross-calibrated with SeaWiFS) and SeaWiFS data onto daily global ocean color maps (Kwiatkoska and Fargion, 2002; Kwiatkoska 2001). The objective of the interpolation was to merge ocean color data sets using individual sensor chlorophyll accuracies and produce error bars for each data point. An addition to conventional statistical objective analysis was proposed to perform both space and time interpolation of ocean color data. Furthermore, the ensemble spatial and temporal correlation structure of the chlorophyll field was made dependent on the ocean spatial variability defined by local dynamical processes. An effort was made to merge ocean color data of different spatial resolutions to support data merger applications focused on local area coverage, such as on coastal zones. A wavelet transform multi-resolution analysis was applied to overlapping MOS and SeaWiFS scenes, where MOS data were at 0.5km resolution and SeaWiFS at 1.1km resolution (Kwiatkoska and Fargion, 2002a & b; Kwiatkoska 2001). The approach enabled enhancement of oceanic features in lower resolution imagery using higher resolution data.

In addition, the SIMBIOS Project developed an operational merged product at the level of observed radiances, water-leaving radiances, or derived products such as chlorophyll. As a demonstration of this technique, software and procedures were developed within the SIMBIOS Project to generate merged Level-3 products from SeaWiFS and MODIS. In coordination with MODIS/Terra oceans collection #4 reprocessing, the SIMBIOS Project began to receive daily Level-3 binned chlorophyll products, and to merge the MODIS products with SeaWiFS Level-3 chlorophyll products within the framework of the SeaWiFS Data Processing System (SDPS) (Figure 1.6). When the first daily binned chlorophyll products from MODIS/Aqua became available, these were immediately incorporated into the merging process as well.

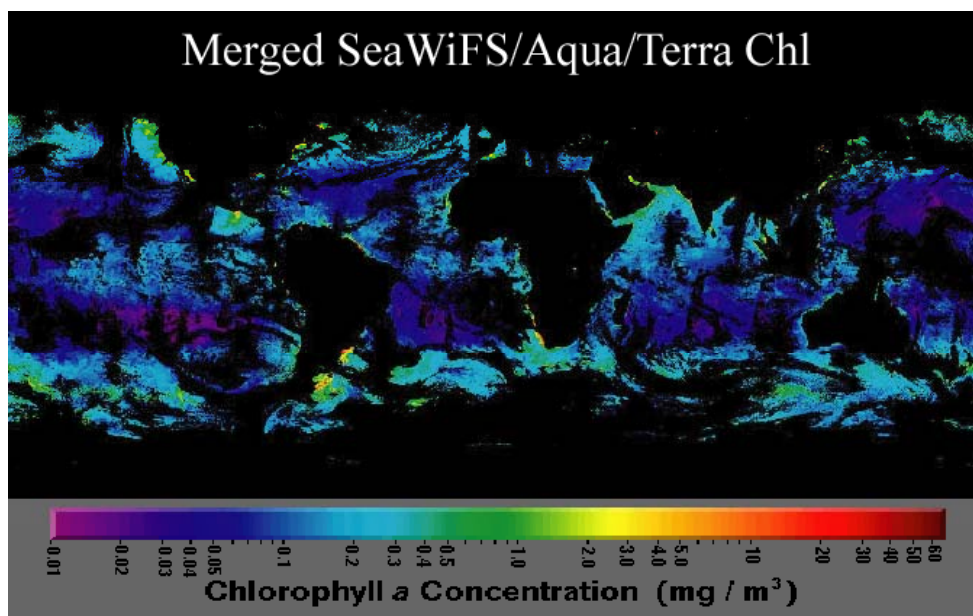


Figure 1.6: MODIS 4.6 km product converted to 9-km SeaWiFS format merged with standard SeaWiFS 9-km Level-3 chlor_a bin product, then mapped.

The SeaWiFS products used in the merging are standard 9-km resolution bin files composited over one-day periods. The MODIS products are standard Level-3 daily binned files at 4.6-km resolution. The specific ocean color parameters used are the chlor_a product of SeaWiFS, which is the chlorophyll concentration derived using the OC4V4 algorithm (O'Reilly, 2000), and the chlor_a_2 product of MODIS (Terra & Aqua), which is the chlorophyll concentration derived with the OC3M algorithm (O'Reilly, 2000). The MODIS product suite includes multiple chlorophyll products, but the chlor_a_2 product is considered to be the SeaWiFS-analog. Both the MODIS and SeaWiFS bin file formats use a sinusoidal distribution of equal area bin elements; however, the MODIS products are generated at a higher resolution

than SeaWiFS. The first step in the merging process is to convert the MODIS products to the 9-km resolution of SeaWiFS, to achieve a 1-to-1 mapping of the MODIS and SeaWiFS bins. The SIMBIOS Project developed two pieces of software to accomplish this task. The first, *modbin2seabin*, converts the MODIS format to a SeaWiFS-like format at the original MODIS bin resolution. This is just a slight reorganization of the Hierarchical Data Format (HDF) fields. The second program, *reduce_bin_resolution*, is essentially a modified version of the SeaWiFS time binning code, which performs spatial compositing of the input bins. For the MODIS files, *reduce_bin_resolution* effectively averages four 4.6-km bins into a single 9-km bin. The averaging is weighted by the square root of the number of observations within each 4.6-km bin, which is the same approach used for standard temporal compositing of MODIS and SeaWiFS (Campbell *et al.*, 1995).

Once the MODIS products have been converted to SeaWiFS-like format and resolution, the standard SeaWiFS temporal binning code, *timebin*, is employed to composite the files from both missions into daily, weekly, and monthly Level-3 bin products at 9-km resolution. Again, the time binner performs a weighted average, with weights computed as the square root of the number of observations within each input bin. These binned products are then mapped using the standard SeaWiFS mapping software, *smigen*, and the mapped files and browse images are distributed through the SeaWiFS Standard Mapped Image browser at <http://seawifs.gsfc.nasa.gov/cgi/level3.pl?DAY=13Jul2002&PER=&TYP=modsea>.

1.5 VALIDATION OF BIO-OPTICAL PROPERTIES

A standard set of measurement protocols is indispensable in developing consistency across the variety of international satellite ocean color missions either recently launched or scheduled for launch in the next few years. The SeaWiFS and SIMBIOS Projects allocated resources to describe and develop protocols or scientific approaches in accordance with the goals of the Projects (Mueller & Fargion, 2003; Fargion *et al.*, 2001). These efforts, described in NASA TMs, are intended to provide standards, which if followed carefully and documented appropriately, will ensure that any particular set of optical measurements will be acceptable for ocean color sensor validation and algorithm development. The protocols are guidelines and may be somewhat conservative. Continued development and refinement of these protocols help ensure coordination, collaboration, and communication between those involved. Furthermore, calibration round-robin intercomparison experiments are conducted by the Project (Riley and Bailey, 1998; Meister *et al.*, 2002 and 2003).

The SIMBIOS and SeaWiFS Projects maintained a local repository of *in situ* bio-optical data, known as SeaBASS, to support and sustain their regular scientific analyses (Hooker *et al.*, 1994; Werdell and Bailey, 2002; Werdell *et al.*, 2003). This system was originally populated with radiometric and phytoplankton pigment data used in the SeaWiFS Project's satellite validation and algorithm development activities. To facilitate the assembly of a global data set, SeaBASS was broadened to include oceanographic and atmospheric data sets collected by the SIMBIOS Project, which aided considerably in minimizing spatial and temporal biases in the data while maximizing acquisition rates. To develop consistency across multiple data contributors and institutions, the SIMBIOS Project also defined and documented a series of *in situ* sampling strategies and data requirements that ensure that any particular set of measurements are appropriate for algorithm development and ocean color sensor validation (McClain *et al.* 1992). The SeaBASS bio-optical data set includes measurements of apparent and inherent optical properties, phytoplankton pigment concentrations, and other related oceanographic and atmospheric data, such as water temperature, salinity, and aerosol optical thickness (AOT). Data were collected using a number of instrument packages from a variety of manufacturers, such as profilers and handheld instruments, on a variety of platforms, including ships and moorings. As of April 2003, SeaBASS included data collected by research groups at 44 institutions in 14 countries, encompassing over 1,150 individual field campaigns, including major international field experiments, such as the Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) and the Indian Ocean Experiment (INDOEX) (Figure 1.7).

The full data set includes over 300,000 phytoplankton pigment concentrations, 13,500 continuous depth profiles, 15,000 spectrophotometric scans, and 15,000 discrete measurements of AOT. Participants of the SIMBIOS Program contributed just over 87% of these data. The SIMBIOS Project Office made use of a rigorous series of submission protocols and quality control metrics that range from file format verification to inspection of the geophysical data values (Fargion *et al.* 2001; Knobelspiesse *et al.*, 2003;

Mueller & Fargion, 2003). This ensures that observations fall within expected ranges and do not exhibit any obvious characteristics of measurement problems. A consistent methodology for validating satellite data retrievals was developed and applied to OCTS, MOS, POLDER, SeaWiFS and MODIS providing a means of objectively analyzing validation results across missions by minimizing the effect of processing differences on the overall results. Briefly, the validation analysis requires coincident measured *in situ* and satellite observations, quality controlled data sets (both satellite and *in situ*), derived from a well-defined, objective set of exclusion criteria (McClain *et al.*, 2000). An example of these validation results for SeaWiFS and MODIS (Terra) are presented in Figure 1.8.

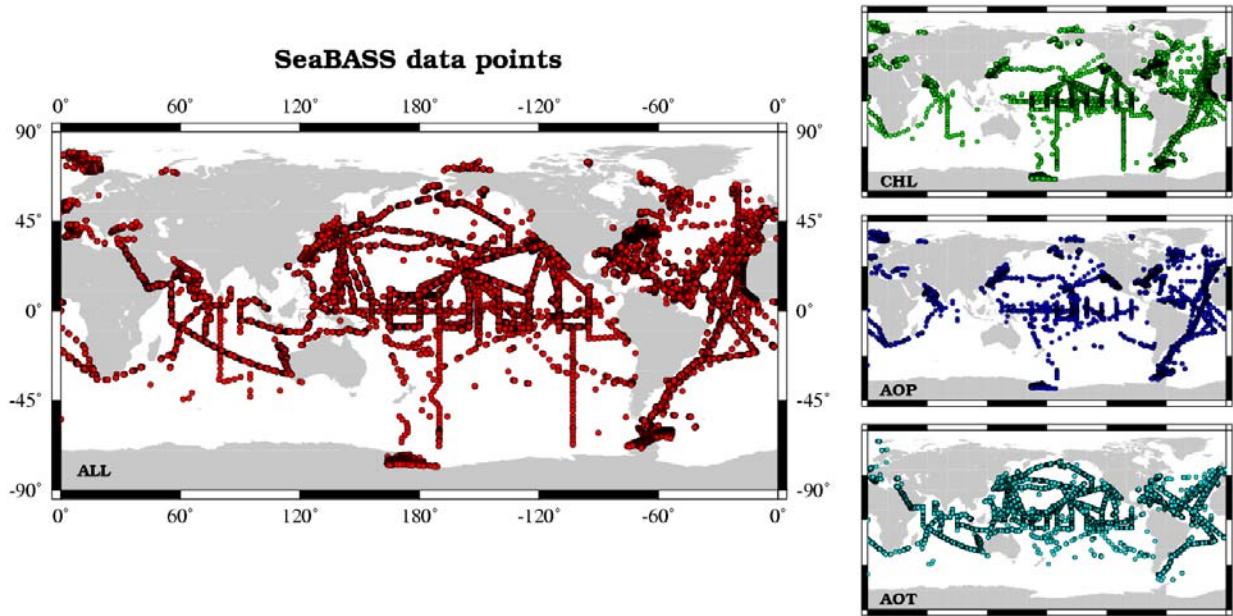


Figure 1.7: The global distribution of data included in the full SeaBASS bio-optical data set, as of April 2003. Clockwise from left: all archived data, chlorophyll *a* concentrations only (CHL), apparent optical properties only (AOP), and aerosol optical thickness only (AOT).

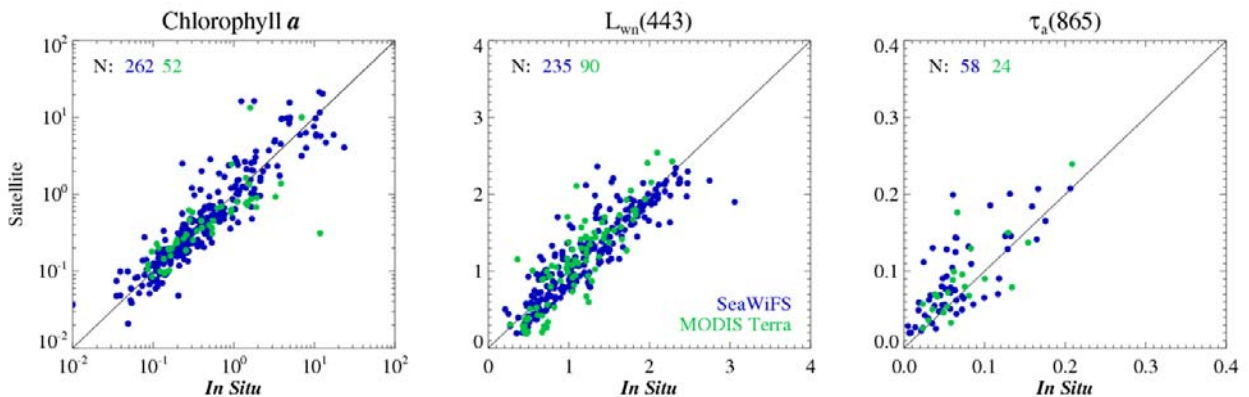


Figure 1.8: Scatter plots of coincident *in situ* and SeaWiFS (blue) and MODIS Terra (green) observations for chlorophyll *a*, water-leaving radiance (L_{wn}) at 443 nm, and aerosol optical thickness (τ) at 865 nm. The chlorophyll *a* data were transformed to account for their log-normal distribution. A one-to-one line has been included for clarity.

The SeaBASS World Wide Web site, located at <http://seabass.gsfc.nasa.gov>, provides a complete description of the system architecture, comprehensive documentation on policies and protocols, and direct access to the bio-optical data set and validation results. Briefly, the architecture consists of geophysical data and metadata recorded in digital ASCII text files, which reside on a dedicated server at NASA GSFC, and a relational database management system (RDBMS) used to catalog and distribute the data and files. Through the use of online search engines that interface with the RDBMS, the full bio-optical data set is queryable and available to authorized users via the Web (Figure 1.9). To protect the publication rights of contributors, access to data collected more recently than January 1, 2000 is limited to SIMBIOS Science Team members, NASA-funded researchers, and regular voluntary contributors, as defined by the SeaBASS access policy (Firestone and Hooker, 2001). The remainder of the data is fully available to the public and, additionally, has been released to the National Oceanic and Atmospheric Administration's (NOAA) National Oceanographic Data Center (NODC) for inclusion in their archive. As of September 2003, 45 research groups outside of the SIMBIOS and SeaWiFS Project Offices have been granted unrestricted access to SeaBASS. In 2002, these groups queried SeaBASS over 950 times and downloaded more than 60,000 data files from the bio-optical data set. During the same period, 146 research groups searched the public set 600 times and downloaded over 37,000 files.

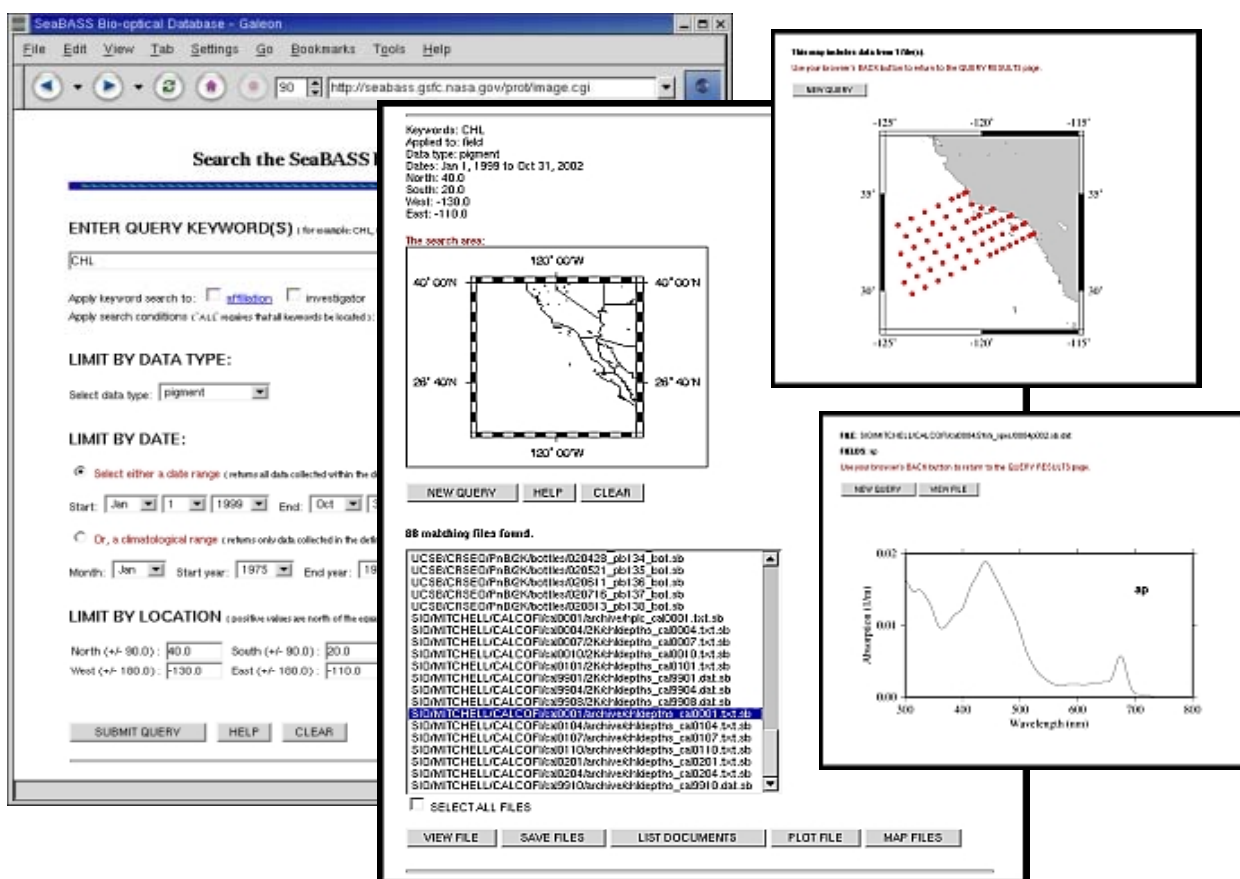


Figure 1.9: The full bio-optical data set is available online, using a variety of search engines and utilities.

1.6 SUPPORT SERVICES

In an effort to improve the quality and quantity of calibration and validation data sets, the SIMBIOS Project offered several support services to field investigators and the larger ocean color community. As of September 1, 2003, 397 cruises have been supported through services provided by the Project. These support services include: scheduling of on-board Local Area Coverage (LAC) recording for SeaWiFS; over

flight predictions for operational sensors; near real time SeaWiFS imagery for cruise locations; satellite data distribution and software support. The Project also provided optical instrumentation from a pool of investigator and project owned instruments; and round robin activities. Detailed information on the services is available on the SIMBIOS web site (<http://simbios.gsfc.nasa.gov/>).

Scheduling SeaWiFS On-board LAC Recording

Since much of the world's oceans are not covered by a SeaWiFS High Resolution Picture Transmission (HRPT) station, high-resolution data may have been recorded onboard the SeaWiFS sensor. As a service to the science community, the SIMBIOS Project, in conjunction with the SeaWiFS Project, scheduled SeaWiFS onboard LAC for cruises that occurred outside HRPT coverage. SeaWiFS has the ability to record a maximum of 10 minutes of high-resolution data per downlink. Typically, a 30-second interval was allotted for each LAC target, which corresponded to 180 scan lines or approximately 200 km along track at nadir.

Overflight Predictions for Operational Sensors

For calibration and validation purposes, *in situ* measurements should be made as close to the sensor over-flight time as possible. To aid investigators in determining when sampling should occur, the SIMBIOS Project offered over-flight predictions for all operational ocean color remote sensors. The sensors supported were SeaWiFS, MOS, Ocean Color Imager (OCI), OSMI, MERIS and MODIS (Terra & Aqua).

Near Real Time SeaWiFS & MODIS Imagery

In addition to providing predictions for satellite over-flight times, the SIMBIOS Project offered near real time imagery of the operational SeaWiFS products and MODIS (Terra & Aqua) to cruises at sea in JPEG and png format. These images may provide useful information in cruise planning both prior to and during oceanographic cruises. Level-1 images are available for SeaWiFS, and Level-2 products for SeaWiFS and MODIS. The SeaWiFS default specifications for the images provided include: available LAC, HRPT, and Global Area Coverage (GAC) (MODIS will be full resolution LAC equivalent); true color images from Level 1 bands 1, 5, and 6 (SeaWiFS only, no true color option available for MODIS); chlorophyll-a (chlor_a_2 algorithm for MODIS); image width 600 pixels; minimum percent valid chlorophyll pixels: 5%; same days as LAC coverage (SeaWiFS only). Images are also customized to best accommodate individual investigator needs.

Satellite Data Distribution

The OCTS is an optical radiometer which flew on the Japanese Advanced Earth Observing Satellite (ADEOS) from August 1996 to June 1997, collecting 10-months of global ocean color data. During the ADEOS mission lifetime, approximately 450 GB of real-time, 700m-resolution OCTS data were collected by the SeaWiFS project through NOAA ground stations at Wallops, Virginia and Fairbanks, Alaska. The archive consists of 337 scenes of the U. S. East Coast and 1,311 scenes over Alaska. These data were processed from raw telemetry through level-2 ocean color products using software developed by SIMBIOS and products distributed through a browse utility linked to the SIMBIOS Project's web site. Furthermore, the entire OCTS GAC data was reprocessed by the Project in 2001. This was a very productive collaboration with NASDA and Japanese scientists. OCTS-GAC data is available through the GSFC DAAC, the SIMBIOS Project and NASDA. Descriptions of the data processing stream, OCTS-specific modification to the algorithms, and statistical comparisons between OCTS and SeaWiFS can be found at: http://seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/OCTS_Repro1/.

Since February 1999, the project has been operating a receiving station at NASA's Wallops Flight Facility (WFF) to acquire data from MOS onboard the Indian IRS-P3 spacecraft. When a pass is acquired at Wallops, the raw files are transferred to the SIMBIOS project at NASA's GSFC via an automated FTP process. The raw files are then converted to level-0 format through a software package provided by the Indian Space Research Organization (ISRO). The resulting level-0 files are made available to the German

Remote Sensing Data Centre (DLR-DFD) for archive and distribution. In addition, the SIMBIOS Project processes the data through level-1B using standard software provided by the German Institute for Space Sensor Technology (DLR-ISST) (Neumann *et al.*, 1995). All MOS data (1999-2003) processed by the SIMBIOS project is made available through the MOS browse system on the SIMBIOS web page.

In coordination with MODIS-Terra Collection 4 reprocessing, the Project initiated an operational process to collect and merge MODIS daily global chlorophyll products with SeaWiFS daily products. The merging scheme is a simple weighted averaging using standard SeaWiFS time-binning software. Presently a complete set of daily, weekly, and monthly merged chlorophyll products, including various perturbations such as MODIS-Terra with MODIS-Aqua, MODIS-Terra with SeaWiFS, MODIS-Aqua with SeaWiFS, and MODIS-Terra/MODIS-Aqua/SeaWiFS are made available at the SIMBIOS web page (<http://seawifs.gsfc.nasa.gov/cgi/level3.pl?DAY=05Mar2000&PER=&TYP=tmsea>). The merging process is fully automated and operational, with new products generated as soon as the MODIS data became available. The merged products can be displayed and manipulated with standard SeaWiFS software tools such as SeaDAS.

Diagnostic Data Set

During the first three SIMBIOS Science team meetings, it was recommended that a “diagnostic data set” be created for each ocean color sensor to aid in comparing data products and to allow rapid reprocessing of selected areas for calibration and algorithm evaluation. Two conditions for the selection of a diagnostic data set site were formulated. First, a reliable source of *in situ* data (bio-optical and/or atmospheric) for the site had to exist, and second, the principal investigator had to be willing to share the *in situ* data with the SIMBIOS project. Sites used as vicarious calibration sources were ranked with the highest priority. Time series sites were ranked as priority 2. All other sites were ranked as priority 3. Several sites were recommended, but did not meet one or both of the defined criteria. Several of the sites were modified, either at the request of an investigator, in order to reduce redundancy or improve coverage (by reducing the amount of land included in the extracted data). The list of sites as currently implemented is found in Table 1.4 and Figure 1.10 shows the MOBY diagnostic site.

By midyear 2001, the SIMBIOS project, in conjunction with the SeaWiFS project, had begun production of the L1A and L2 subsets of SeaWiFS LAC resolution data for the list of diagnostic data set sites. Prior to the start of the Collection 4 reprocessing of MODIS (Terra) data in March of 2002, the SIMBIOS project approached the MODIS Oceans Team with the request that MODIS produce a comparable set of extracted L1 and L2 data for inclusion in the diagnostic data set. The MODIS team agreed. However, as a consequence of the flow of data through MODAPS (the MODIS Adaptive Processing System), MODIS Oceans provides L1B and L2 extracts, rather than L1A as was the recommendation of the SIMBIOS Science Team and IOCCG Working Group. The diagnostic data set files produced by MODAPS are sent to the SIMBIOS project for post processing. In order to ensure that only useful data are included in the diagnostic data set, a threshold on the number of valid pixels within the region of interest was set. If this threshold (currently 25%) is not met, the files are excluded from further processing. If the threshold is met, a L2 (chlorophyll) browse image and two TAR files are created: one TAR file for the L2 granules and one for the L1B granules. Since the MODIS data are produced in five minute granules, the region of interest for a given site may cross the boundary between two granules. When this occurs, all L2 products from both granules are placed in the same TAR file, likewise for the L1B granules. The TAR files are then compressed using gzip compression.

The SIMBIOS and MODIS teams worked with the Goddard Distributed Active Archive Center (GDAAC) to make the diagnostic data set files for SeaWiFS and MODIS (Terra and Aqua) available through the GDAAC. All the necessary mechanisms for the transfer of the dataset to the GDAAC have been put in place, the most critical of which was the creation of six new Earth Science Data Type (ESDT) definitions, one for each L1 and L2 data type as well as for the SeaWiFS, MODIS-Terra and MODIS-Aqua data sources. Once the data are archived at the GDAAC, they are visible to both the GDAAC WHOM search engine and the EOSDIS EDG search engine. The diagnostic data set allows for the rapid processing and testing of atmospheric correction and geophysical product algorithms. The current list of sites cover a wide range of water types and aerosol conditions (see Table 1.4), which will aid algorithm assessments.

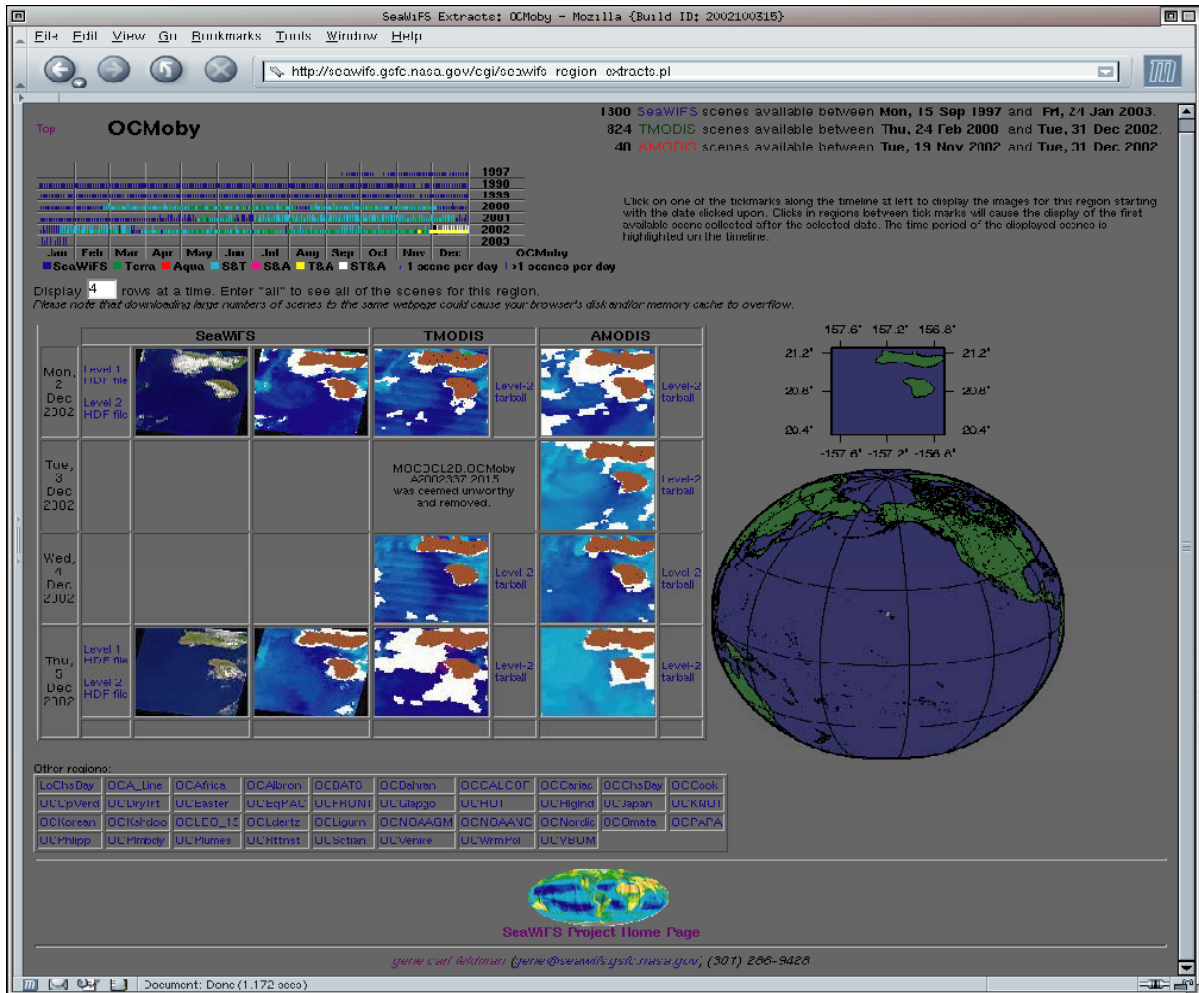


Figure 1.10: MOBY diagnostic site

SEADAS Software

The SeaDAS is a comprehensive software package for processing, displaying and analyzing all SeaWiFS data products (<http://seadas.gsfc.nasa.gov>). It was designed to serve a wide range of users, including individual scientists, SeaWiFS ground stations, and operational or commercial users. SeaDAS also provides level conversion processing designed to accurately replicate the operational data products (geophysical fields and data formats) generated by the SeaWiFS Project, when using the default input values. In addition, SeaDAS allows for flexibility in the algorithms applied, the map projections used, and other aspects of processing and analyses that enable users to customize their data products. Flexibility is further enhanced by providing executable programs, for those who only need the basic capabilities, and source code, for those who wish to insert alternative algorithms. The SeaDAS software package contains a full suite of interactive display and basic analysis tools. The SeaDAS tool kit includes many navigation, display, analysis, and output functions. Navigation functions include data registration, map projections, overlaying of coastlines, plotting of *in situ* data, and latitude/longitude point location. General display functions include data scaling, color bar definition, annotation, zooming, roaming, and color palette manipulation. General analysis functions include bathymetry generation, simple arithmetic functions, contour plots, profile plots, scatterplots, and histograms. Output functions allow output of either data or latitude/longitude values (ASCII, HDF, and binary flat files formats) or displayed images (PNG and PostScript formats). The SeaDAS group is co-located with the SeaWiFS and SIMBIOS Projects. SeaDAS was augmented by the SIMBIOS Project to include OCTS, MOS, OSMI, and soon, MODIS. The current SeaDAS user community includes approximately 500 research sites in 45 countries.

Table 1.4 Diagnostic site ID and location

Site ID	Location	North latitude	South latitude	West longitude	East longitude	Contact PI
OCAIbron	Alberon Gyre Eastern Med.	33.5N	32.5N	32.0 E	33.0E	
OCA Line	Japan East coast	42.0 N	41.0N	145.283E	146.283E	Tsuda
OCAfrica	Mauritanian Upwelling	21.5N	20N	18W	17W	Carder
OCBahrain	Bahrain, Persian Gulf	26.816 N	25.816N	50.0 E	51.0E	
OCBATS	BATS Bermuda	33.0N	31.0N	65.5W	63.5W	Nelson
OCCALCO F	CALCOFI, California Coast	34.5N	30.5N	124.0W	122.0W	Mitchell
OCCpVerd	Capo Verde, NW African Coast	17.217N	16.217N	23.433W	22.433W	Carder
OCCariac	Cariaco Basin, Venezuela	11.0N	10.0N	65.66W	64.16W	Mueller- Karger
OCChsBay	Chesapeake Bay	39.5N	36.8N	76.8W	75.6W	Harding
OCCook	Cook Island, Western South Pacific	19.5S	20.5S	163.5W	162.5W	
OCDryTrt	Dry Tortugas, Florida Keys	21.1N	24.1N	83.283W	82.283W	Voss
OCEaster	Easter Island, South Pacific Gyre	26S	28S	116W	114W	SIMBIOS Project
OCEqPAC	Eastern Equatorial Pacific	0.5N	0.5S	155.5W	154.5W	Chavez
OCFRONT	Long Island, New York	41.45N	40.45N	72.5W	71W	Morrison
OCGlapgo	Galapagos Islands	2.13N	1.87S	98.81W	88.81W	Feldman
OCHattrrs	Cape Hatteras	37.5N	34.5N	76.5W	73.5W	Stumpf & Cota
OCHlgld	Helgoland, North Sea	54.6N	53.6N	7.3E	8.3E	
OCHOT	HOT Station, Hawaii	23.25N	22.25N	158.5W	157.5W	Letelier
OCKshdoo	Kaashidoo, Maldives Islands	5.45N	4.45N	72.95E	73.95E	Holben & Frouin
OCKNOT	KNOT Station, NW Pacific	44.5N	43.5 N	154.5E	155.5E	Saitoch
OCKorean	Korean seawater Monitoring site, East China Sea	32.5N	31.5N	124.5E	125.5E	Kim
OCLeo 15	LEO 15 Station, New Jersey	40.1	38.5N	74.75W	73.5W	Arnone
OCLigurn	Ligurian Sea, Mediterranean	43.87 N	42.87 N	7.4 E	8.4 E	Antoine
OCLderz	Luderitz Upwelling, Namibian Coast	25.5S	26.5S	14E	15E	
OCMOBY	MOBY Buoy, Hawaii	21.3N	20.3N	157.75 W	156.7W	Clark & Trees
OCMontry	Monterey Bay,	37N	36.5N	122.75W	121.75W	Chavez

	California					
OCNOAAG M	Northern Gulf of Mexico	30N	29N	88W	87W	Arnone
OCNordic	Baltic Sea	55.5N	54.5N	18.8E	19.8E	
OCPAPA	Station PAPA, North Pacific	52 N	48 N	147 W	143 W	
OCPhlipp	Philippines	17.5 N	16.5 N	132.5 E	133.5 E	
OCPlumes	Plumes and Blooms region, Santa Barbara, CA	35.5 N	32.5 N	122 W	118 W	Siegel
OCplymbdy	PlyMBoDY Mooring, English Channel	50.4 N	49.6 N	4.8 W	3.4 W	Aiken
OCRttnst	Rottnest Island, Western Australia	31.3 S	32.3 S	114.8 E	115.8 E	Lynch
OCScian	Scotia Prince Ferry Route, Gulf of Maine	43.8N	42.8N	70.25W	65.75W	Balch
OCTahoe	Lake Tahoe	39.671N	38.671N	120.604W	119.604W	
OCVenice	Venice Tower (AAOT) Northern Adriatic	45.6N	44.8N	12.2E	13.4E	Zibordi
OCWrmPol	Warm Pool, Western Equatorial Pacific	0.5N	0.5S	164.5E	165.5E	
OCYBOM	YBOM replacement mooring, East China Sea	24.89N	23.89N	122.77E	123.77E	Ishizaka

Instrument Pool

Over the the years the Project has maintained and deployed a pool of sun photometers and above water radiometers intended to complement in-water optical measurements as well as the land-based Aerosol Robotic Network (AERONET) sun photometer network. The overall goal was to study aerosol optical properties and validate satellite retrievals of aerosol optical properties.

Three types of instruments composed the instrument pool (<http://simbios.gsfc.nasa.gov/Sunphotometers/>). The first type was a sun/sky photometer that measured the solar irradiance and the sky radiance. The second type was the shadow-band radiometer that measured the diffuse and total sky radiance. The third type was the Micropulse Lidar (MPL), which measured the vertical and horizontal distribution of aerosol backscatter, extinction and optical depth. The instruments were deployed by SIMBIOS or NASA principal investigators on cruises and the collected data was archived in SeaBASS. This instrument pool included fourteen Microtops II sun photometers (Morys *et al.*, 2001), one SIMBAD and two SIMBADA above water radiometers/sun photometers (Deschamps *et al.*, 2003), 2 PREDE sun photometers and one micro-pulse Lidar. The description, characteristics and advantages of each instrument have been reviewed in project protocols and project annual reports.

In addition to the instrument pool, the Project augmented the existing AERONET, which is dedicated to monitoring aerosol optical thickness (AOT) around the globe by supplying additional CIMELS. Most of the sun photometers used within the AERONET project (Holben *et al.*, 1998) are in continental zones, and SIMBIOS enhanced this network with island and coastal stations (Figure 1.11). SIMBIOS CIMEL sites included Lanai Hawaii (with backup in Honolulu, USA), Ascension Island, Bahrain, Papeete (Tahiti), Wallops Island (USA), Anmyon Island and Chinae (South Korea), Erdemli (Turkey), Horta (The Azores), Puerto Madryn (Argentina), Dahkla (Morocco) and Rottnest Island (Australia). This deployment activity ended in 2001 and all instrument are now managed by the AERONET group. SIMBIOS coastal stations have been used by the atmospheric community and their data have been used in several scientific papers.

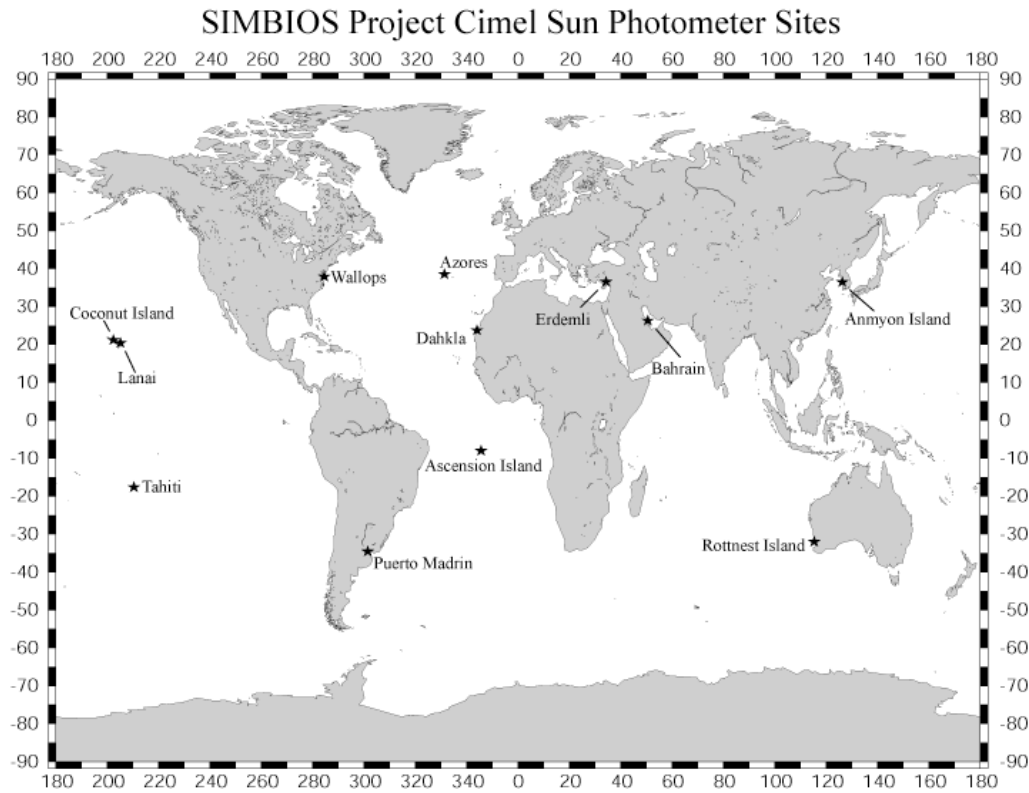


Figure 1.11: SIMBIOS CIMEL coastal and island sites.

SIMBIOS Project has taken a number of steps to ensure the consistency and quality of this atmospheric data set. Calibration was performed approximately every three months. Details on the operation, calibration and theoretical principles of sun photometry are posted at <http://simbios.gsfc.nasa.gov/Sunphotometers/principle.html>. To aid the organization and dissemination of collected data, the sun photometer instrument pool web site posts information about the deployment and data processing status of each instrument, along with calibration coefficient histories (Figure 1.12).

Several steps were taken to ensure data quality consistency from several instrument designs (Figure 1.13). The ACE-Asia cruise, on the R/V Ron Brown, was an ideal platform to validate SIMBIOS sun photometers. The R/V Ron Brown, which departed from Hawaii on March 15, 2001 and arrived in Yokosuka, Japan on April 19, 2001, encountered a variety of aerosol types, from maritime low optical thickness conditions to extremely high optical thickness due to Asian dust. Visual inspections of data time series suggest that despite differences in instrument design, calibration and deployment, AOT and Ångström exponent typically agree within uncertainties. Data from instruments whose bands (1) have similar (within 10nm) center wavelengths, and (2) have calculated uncertainty values were analyzed to find measurements taken within fifteen minutes of each other. These temporally similar measurements were plotted to assess trends or biases between the data. Nearly all AOT and Ångström exponent data fall within one uncertainty unit of the 1:1 line (data not shown). Generally speaking, at least 70% of all AOT data compare within one uncertainty unit of the value from another instrument, with the best agreement between the hand held instruments. With its high uncertainty values, the Ångström exponent comparisons are even better, at 90% or more. Other problems, such as sun pointing for the Microtops II, were resolved by modifying the measurement protocols (Knobelspiesse *et al.*, 2003) and performing an uncertainty analysis for each instrument. Uncertainty values were computed and archived for each AOT and Ångström exponent measurement (Deschamps *et al.*, 2003; Russell *et al.*, 1993; Miller *et al.*, 2003). Computation of the Ångström exponent, which expresses the spectral character of the AOT values measured by sun

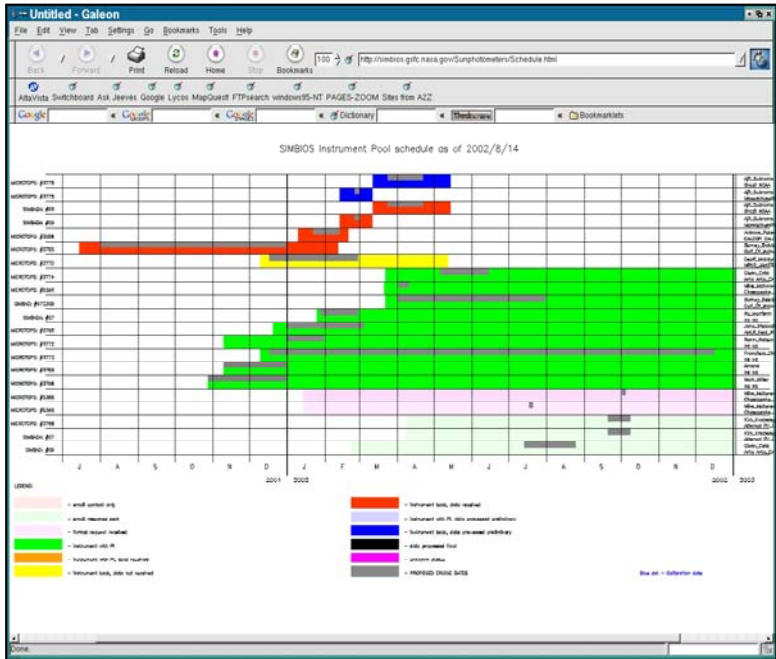


Figure 1.12: Instrument schedule for the pool deployment, calibration and data processing.

photometers, was standardized using multiple bands and a linear fitting routine to paired wavelength and natural logarithm of AOT values. The Ångström exponent is the negative slope of this fit. This Ångström exponent calculation method uses a recursive routine that makes an analytical computation of uncertainty impossible. To account for this, an Ångström exponent calculation method was devised that incorporates the individual AOT uncertainties and the Chi-square error to determine and Ångström exponent

uncertainty. For several years the Project collected, processed and archived optical aerosol data from handheld sun photometers in marine locations. After standardizing the data processing of MicroTops and SIMBAD/A by using identical calibration methods, ancillary data and processing software, a statistical analysis was done (Knoblespiesse *et al.* 2003b). Statistical analyses reveals a dataset influenced by its temporal and geographical distribution, while the multi-modal histogram for AOT and Ångström exponent reveal varied aerosol populations (Knoblespiesse *et al.* 2003). This separation was validated by showing individual classes more likely to be log-normally (for AOTs) or normally (for Ångström exponents) distributed than the dataset as a whole. Properties of each class are represented in Figure 1.14. Results are also compared with the SeaWiFS atmospheric correction-aerosol models (Figure 1.15). The implications of this comparison are discussed in Knoblespiesse *et al.* (2003b) and in Chapter 19 by M. Wang.

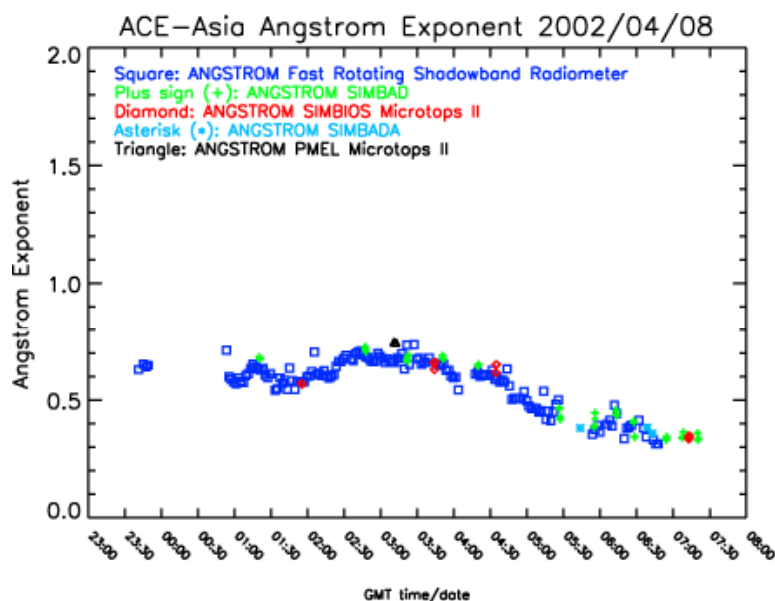


Figure 11.3: Validation of the SIMBIOS sun photometers on the ACE-Asia cruise.

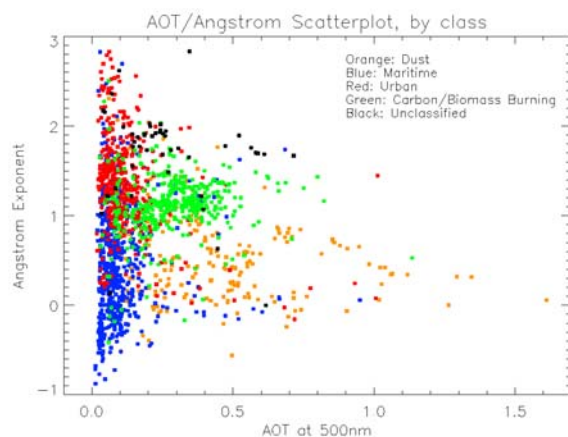


Figure 1.14: Location on an AOT/Ångström Exponent scatter plot of each class. Data in blue represent class 1 type aerosols, encountered in 'maritime' conditions, while orange represents class 2 'dust', green shows class 3 aerosols and red represents class 4 aerosols encountered in 'urban' conditions. Data in black could not be classified.

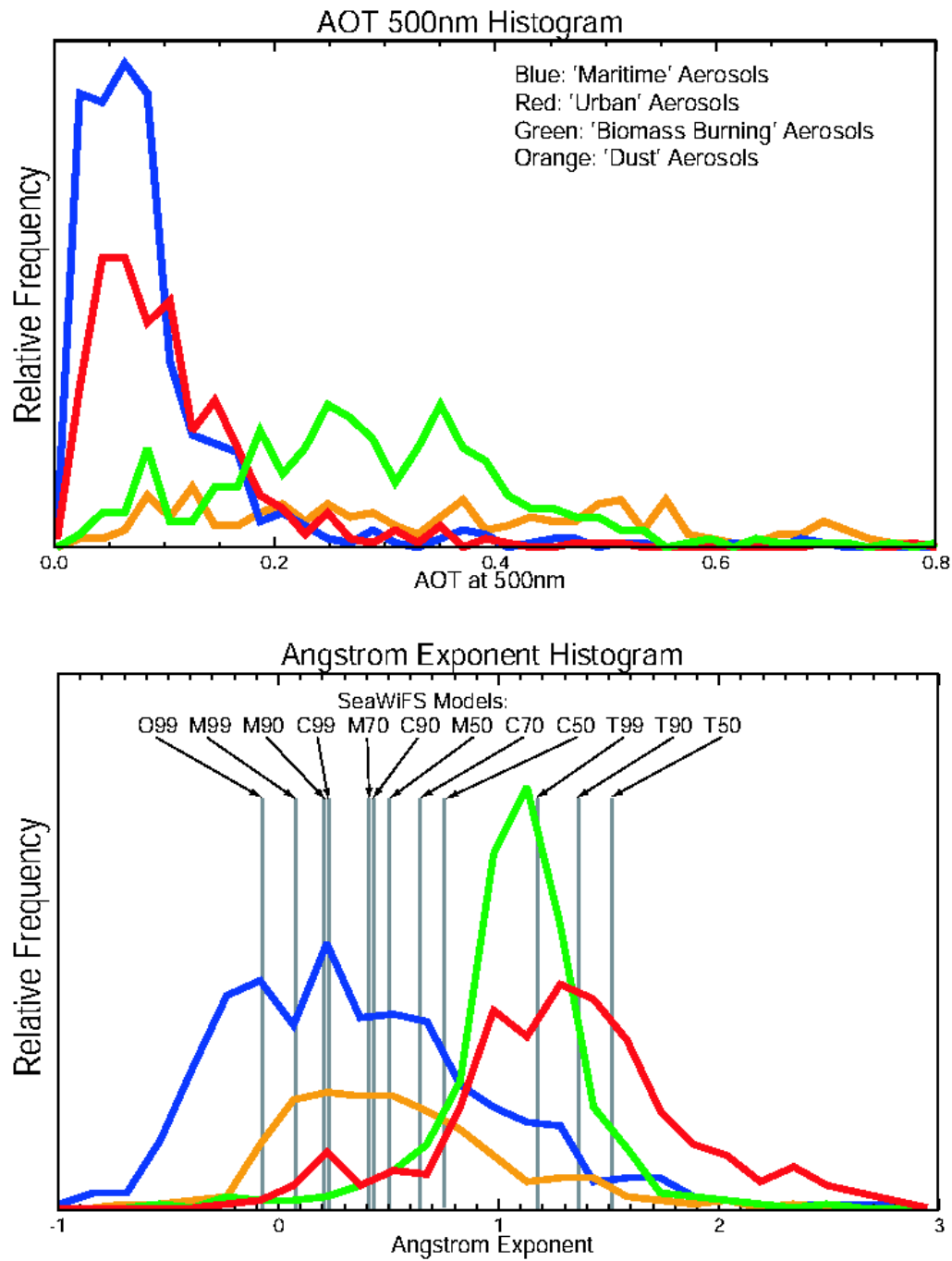


Figure 1.15: Histograms of AOT at 500nm and Angstrom Exponent for classified aerosol data. Class 1 is presented in blue, class 2 in orange, class 3 in green and class 4 in red. Bin sizes used in histogram computation were 0.02 for AOT at 500nm (A) and 0.1 for Angstrom Exponent (B). Vertical black bars on the Angstrom Exponent histogram show the equivalent Angstrom Exponents for SeaWiFS aerosol models (Gordon and Wang, 1994), (Shettle and Fenn, 1979).

1.7 CALIBRATION ROUND ROBIN

Two kinds of activities were performed by the Project to further ensure the adequate quality of *in situ* data. First, as mentioned, measurement protocols were developed, and their usage by the science community encouraged. Second, calibration round robin intercomparison experiments were conducted. The first SeaWiFS Transfer Radiometer (SXR) was built for the SeaWiFS Project to verify and compare measurements of spectral radiance at six discrete wavelengths in the visible and near infrared (Johnson *et al.*, 1998). The SXR is currently used to compare these sources to standards of spectral radiance maintained at the National Institute of Standards and Technology (NIST). The SIMBIOS Project had a second copy of the SeaWiFS Transfer Radiometer (SXR-II) built for use in the calibration round robin. This unit supplemented the first unit and was designed for easier travel. NASA personnel executed the first SIMBIOS-sponsored calibration round-robin experiment (the sixth SeaWiFS Intercalibration Round-Robin Experiment or SIRREX-6; previous round-robin had been sponsored by the SeaWiFS Project) from August 1997 to February 1998 (Riley and Bailey, 1998).

In SIRREX-6, four common field instruments (Satlantic in-water radiometers) were taken to nine separate laboratories and tested using the laboratories' standards and procedures. Two of the sensors were seven-channel radiance heads and two were seven-channel irradiance heads. The calibration and data reductions procedures used at each site followed the laboratories' normal procedures. The reference lamps normally used for the calibration of these types of instruments by the various laboratories were also used for this experiment. Project personnel processed the data to produce calibration parameters from the various laboratories for comparison. These tests showed an overall agreement at better than the $\pm 2\%$ level. The SIRREX-6 was followed by the SIMBIOS Radiometric Intercomparison experiments (SIMRIC-I and II) in 2001 and 2002 (Fargion and McClain, 2003; Meister *et al.*, 2002; Meister *et al.* 2003). The purpose of these round-robins was to: 1) verify that all laboratories were on the same radiometric scale; 2) detect and correct problems at any individual laboratory in a timely fashion; 3) encourage the common use of calibration protocols; 4) identify areas where the calibration protocols need to be improved; and 5) document the calibration procedures specific to each laboratory. The participating laboratories included academic institutions, government agencies and instrument manufacturers that either directly or indirectly contributed to SeaBASS. They were, in alphabetical order: Biospherical Instruments Inc.; HOBI Labs Inc.; ICESS at the University of California, Santa Barbara; MOBY Project of Moss Landing Marine Laboratories; NASA Code 920.1, Goddard Space Flight Center; NASA Code 972, Wallops Flight Facility; Naval Research Laboratories, Washington; Satlantic Inc., Canada; Scripps Institute of Oceanography, University of California, San Diego; University of Miami; University of South Florida, St. Petersburg.

The SXR-II was calibrated on a yearly basis at NIST, in the Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) facility. The radiometric stability of the SXR-II between NIST calibrations was monitored by the portable light sources the SeaWiFS Quality Monitors (SQM), the OCS-5002 from YES, Inc., and the SQM-II from Satlantic, Inc. The radiances produced by the laboratories for calibration were measured in the six SXR-II channels from 411 nm to 777 nm and compared to the radiances expected by the laboratories. Typically, the SXR-II measured radiances differed from the radiances expected by the laboratories by less than 2%. This level of agreement is satisfactory. In some cases, larger deviations were found and tracked to issues such as improper baffling, incorrect setup of the light sources, or deterioration of the main calibration bulb of the respective laboratory. Several issues were identified where the calibration protocols needed to be improved, especially the reflectance calibration of the reference plaques and the distance correction when using the irradiance standards at distances greater than 50 cm.

1.8 CONCLUDING REMARKS

Past and present satellite missions typically provide observations that are limited to the short-term, to specific processes of scientific interest or to test new technologies. Production of long-term products requires cross-calibrated measurements that have been merged in space and time measurements. The production of these products is usually beyond the scope of individual missions. SIMBIOS Program goals and tasks addressed the complexity of issues involved with how to produce a long-term calibrated data set across missions for use in climate research.

The specific objectives of the SIMBIOS Program were: (1) to quantify the relative accuracy of measurements from the ocean color products from each mission, (2) to work with each project to improve the level of confidence and compatibility among these products, and (3) to develop methodologies for generating merged level-3 products. Clearly, these objectives encompass both experimental and operational requirements. The Project has established links with all of currently operational missions (1997-2003) and has built up an operational project with the activities described in Figure 1.1. These activities build on the “*know how*” and experience of the SIMBIOS and SeaWiFS inhouse staff. One of the SIMBIOS Project’s unique capabilities is to address the complexity of all the characterization and calibration processing steps as a “*start to finish*” process. This approach is a success story on how to tackle these issues while engaging the ocean color community. An open, peer review process within the Project staff and with the larger ocean color community on algorithm development, merging techniques and protocol development is the valid model for the operation of future missions.

The following specific conclusions may be drawn from the SIMBIOS experience: simple merging techniques (big bin or other averaging methods) applied on known biases result in degradation of merged data set and is not recommended; cross calibration and characterization in time and space with overlapping periods are essential steps before proceeding with data set merging or producing long time series; neural network and semi-analytical merging algorithms can produce merged products with lower uncertainties while providing the desired improvements in daily coverage, and both methods require *a priori* knowledge of the uncertainty and characterization over time of the merged missions; the funded global *in situ* bio-optical collection and SeaBASS data set have been invaluable resource for evaluating satellite products and data merging methodologies and it, or a similar data set, is required for further efforts.

The achievements were certainly due to the well thought out tasks (accurate characterization, calibration, establishment of traceability by national measurement institutions, validation, etc.) and operational configuration (Figure 1.1). Over the past several years, a set of key resources were developed:

- a comprehensive *in situ* bio-optical database;
- a program to evaluate different atmospheric correction algorithms;
- a program to link the calibrations of individual ocean color satellite instruments;
- a program (including cross-calibrations and measurement protocols) to develop a consistent *in situ* calibration and validation data set for the satellite measurements;
- a model for funded collection of *in situ* data, including rapid turn around;
- alternate algorithms to convert radiometric measurements to derived geophysical products;
- alternate methods to combine ocean color measurements from different sources into a single data set; and
- a strong documentation record.

The calibration and validation programs for individual missions (both domestic and international) had a wide range of approaches and methodologies, making international cooperation imperative to ensure high quality climate data. Calibration of long-term, high quality data, mission data overlap and consistent data sets are the basis of data stability. Natural signals are very small and impossible to detect with unstable and/or gappy data. Further data stability requires a system that should have the capability to reprocess large data sets as our understanding improves. Our hope is that the organizational structure, lessons learned, and knowledge achieved by SIMBIOS will benefit future ocean color programs. Finally, and perhaps most importantly, the SIMBIOS program demonstrated that international projects, agencies, and science teams could work effectively together in tangible ways (e.g., sharing data, processing code, algorithms, and product evaluations, and in collaborating on joint mission reprocessings) to improve the products each mission was generating and to generate a high quality time series of global observations.

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